# NATIONAL ADVISORY COMMITTEE
# FOR AERONAUTICS

### TECHNICAL NOTE

### No. 1007

BOUNDARY-LAYER-CONTROL TESTS OF TWO WINGS

IN THE LANGLEY PROPELLER-RESEARCH TUNNEL

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SUMMARY

Tests of two wings were made in the Langley propeller-research tunnel to determine the increase in lift obtainable by boundary-layer control and to determine the power required for the blower. One wing, designated the stub wing, had a 6.5-foot span, a 5.5-foot chord, and a maximum thickness of 0.30 chord and was fitted with large end plates; the second wing was an NACA 2415 airfoil of 16-foot span and 2.67-foot chord and was tested without a flap, with a plain flap, and with a Zap flap.

Lift coefficients of about 3.2 were obtained for the stub wing either by the suction or the pressure method, but the pressure method required several times more power than the suction method. The best slot location for this wing was found to be near the midchord position. A single suction slot was more effective than any multiple slot arrangement when the same pressure was applied to all slots.

For the NACA 2415 wing, which was tested only with
suction, the best slot position was between 0.11 and
0.20 chord from the leading edge for either the plain
wing or the wing with a Zap flap. For the wing with a
plain flap, a slot on the flap just behind the hinge
required least suction power and provided high maximum
lift coefficients at angles of attack in the practical
range. Slots near the flap hinge appear to be effective
in maintaining high lift-curve slope and high flap effec-
tiveness, but those near the leading edge are more
effective in holding the flow at high angles of attack.
Maximum lift coefficients were about 2.8 for the plain
flap and about 3.1 for the Zap flap. Some tests of the
plain wing with a slot at 0.91 chord showed an appreciable
increase in the lift-drag ratio (where the drag included
the blower drag) for the take-off and climb range.


INTRODUCTION


Boundary-layer-control tests made with small models
at the Langley Laboratory (reference 1) and elsewhere
(reference 2) have shown that control of the boundary
layer offers a powerful means of increasing the maximum
lift and the range of angles of attack for safe flying.
In the work for the present report large model wings
were tested in the Langley propeller-research tunnel in
an effort to obtain more information on the practica-
bility of the method.

One set of tests was made of a stub wing of 6.5-foot
span, 5.5-foot chord, and a maximum thickness of 0.30 chord,
fitted with large end plates to increase the effective
aspect ratio and to make the flow more nearly two-
dimensional. The great thickness and short span facili-
tated the tests because the blower could be installed
directly inside the wing and because the mechanical work
involved in making changes would be simplified. For the
second set of tests a conventional wing of aspect ratio
6, 16-foot span, and thickness of 0.15 chord was used,
arranged above a "fuselage" in which the blower was
housed. This wing was also tested with plain and with
Zap flaps.

## MODELS AND TESTS.

For the first series of tests, the stub wing and the arrangement of the end plates are shown in figures 1 and 2, and the airfoil ordinates are given in table I. Boundary-layer control on this wing was effected both by sucking the boundary layer into the wing through spanwise normal-opening slots and by discharging air through spanwise backward-opening slots. (See fig. 3.) Various slot locations, slot sizes, and wing internal pressures were tried in both cases. The motor-driven blower served for both types of boundary-layer control and inducted or discharged the air through the end of the wing.

The conventional wing used for the second series of tests had a 2.67-foot chord with the NACA 2415 airfoil section (fig. 4). This wing was tested only with suction, and the blower discharged the inducted air through the rear of the fuselage. The wing was fitted with a 0.30-chord full-span hinged trailing-edge flap that could be deflected $15^\circ$, $30^\circ$, $45^\circ$, or $60^\circ$. A removable 0.25-chord full-span Zap flap was also tested, but at only one flap angle ($50^\circ$ to the chord line).

For the stub-wing tests the airspeed was approximately 40 miles per hour. For the NACA 2415 wing of aspect ratio 6, the airspeed was reduced to about 30 miles per hour for most of the tests in order to attain large ratios of wing pressure to dynamic pressure with the low blower power available. A few tests were also made at an airspeed of approximately 80 miles per hour to determine the effect of boundary-layer control on the drag characteristics, especially in the range of lift coefficients corresponding to the take-off and climb conditions.

## SYMBOLS

c      airfoil chord

b      airfoil span

$V_o$      free-stream velocity

$p_o$      free-stream static pressure

$q_0$        free-stream dynamic pressure

$H_b$       total pressure inside wing

$Q$        volume rate of flow through slot; positive for flow entering the slot

$P$        power input to blower

$C_L$       lift coefficient

$C_D$       drag coefficient

$C_{D_i}$       induced drag coefficient

$C_{H_b}$       internal wing pressure coefficient $\left(\dfrac{H_b - P_0}{q_0}\right)$

$C_Q$       volumetric coefficient $\left(\dfrac{Q}{V_0 cb}\right)$

$C_{D_{b(ideal)}}$       ideal-blower drag coefficient $\left(C_Q\left(1 - C_{H_b}\right)\right)$

$\Bigg(C_{D_{b(ideal)}}$ is the drag coefficient equivalent to the power required (100-percent blower efficiency assumed) (1) for suction slots, to discharge, at free-stream total pressure, air withdrawn from the boundary layer and (2) for pressure slots, to increase the pressure of the incoming air, assumed to enter with the free-stream total pressure, enough to discharge the desired quantity of air into the boundary layer at a given total pressure $H_b$ $\Bigg)$

$C_{D_b}$       blower drag coefficient; drag coefficient equivalent to power input to blower $\left(\dfrac{P}{q_0 bcV_0}\right)$

$C_{D_T}$       total drag coefficient $\left(C_D + C_{D_{b(ideal)}}\right)$

The blower drag coefficient $C_{D_b}$ is used for convenience in comparing results of several of the present tests; however, the ideal blower drag coefficient is used when comparisons with results of other investigations are made.

## RESULTS AND DISCUSSION

### Stub Wing

Pressure slots.- Typical lift curves for a backward-opening pressure slot on the stub wing are shown in figure 5 for four values of the wing pressure coefficient and are compared with the lift curve for the wing without boundary-layer control. The low lift-curve slope resulted from the low effective aspect ratio of the wing. For an aspect ratio of 6, a lift coefficient of 3.0 would occur near 30° angle of attack as determined by extrapolating the curve for $C_{H_b} = 10.20$ (fig. 5) to zero lift and computing the angle of attack for the new aspect ratio. In figure 6 the maximum lift coefficient is plotted against blower drag coefficient for each slot. Within the range tested the 0.0075c slot at 0.42c appears to require the smallest blower drag coefficient for a given maximum lift.

Single suction slots.- Typical lift curves for the stub wing with single suction slots are shown in figure 7, and plots of maximum lift coefficient against blower drag coefficient for each slot are shown in figure 8. The most interesting features of the curves are the low pressure coefficients $C_{H_b}$ and the low blower drag coefficients $C_{D_b}$ required in comparison with those for the pressure slots (figs. 5 and 6). Of the slots tested, the most efficient appear to be the 0.03c, 0.045c, and 0.06c suction slots at 0.54c. The highest maximum lift coefficient (3.2) was obtained with a 0.061c slot at 0.54c with a blower drag coefficient of 0.07. Nearly the same lift coefficients were obtained with a pressure slot at 0.42c, but the blower drag coefficient was several times as much. A few tests, for which the data are not shown, were made with a 0.015c forward-opening suction slot at 0.50c; these slots were found to require less blower power than the best pressure-type slot but more than the best normal-opening suction slot.

Multiple slots.- A few multiple-slot arrangements were tried with both methods of control. The results for the best of each type are shown in figure 9. Each arrangement shown had two slots, except one that had 23 very narrow slots spaced 0.03c apart. None of these arrangements appears as favorable as the best single suction slot.

Comparison of results of stub-wing tests.- In figures 10 and 11, respectively, the maximum lift coefficient of the stub wing is plotted against ideal-blower drag coefficient and volumetric coefficient for the most efficient of the arrangements tested. In figure 11 the curve for the slot at 0.54c shows that the volume of air required to obtain a given lift coefficient is independent of the slot width. For comparison, results are also shown for the 0.15c wing tested with pressure control in reference 1 and for the 0.40c wing tested with suction control in reference 2. As already indicated, the suction slots are seen to be several times more efficient than the pressure slots, because they require both smaller pressure coefficients and smaller volumetric coefficients. The comparison with the results for the wing of reference 1 is merely a further example of the fact that boundary-layer control increases maximum lift more easily on a thick wing than on a thin wing.

## NACA 2415 Wing

Slot taper.- Only the suction type of slot was tested on the NACA 2415 wing of 16-foot span. With a large span and a comparatively thin wing, some difficulty in obtaining uniform spanwise distribution of the quantity of air sucked off was anticipated because of the flow losses inside the wing and the increase in the velocity of flow from the tip to the center of the wing. This distribution presumably would be uniform if the product of the slot width and the square root of the pressure difference across the slot were uniform. For this series of tests, the slot that was used for all wing configurations was tapered from a width of 0.0234c at the center to 0.0350c near the tip - an arrangement that satisfied the proposed criterion for a high-lift condition of the plain wing. It should be noted that, even with a tapered slot, the thin wing is handicapped because an excess suction must be provided throughout the span in order to provide the minimum suction required near the wing tip.

Plain wing.- Lift curves for the plain wing are shown in figure 12 for six slot locations. The blower speed was constant for these curves and the blower input power approximately so. Figure 13 shows maximum lift coefficient for the same slots plotted against ideal-blower drag coefficient. The best slot location appears to lie between 0.11c and 0.20c from the nose; for this

location, the maximum lift coefficient 2.6 is obtained
with an ideal-blower drag coefficient of approximately 0.3.
The slot effectiveness decreases steadily as the slot is
moved toward the trailing edge.

Wing with plain flap. - Two slot locations were
tried for the tests of the wing with the plain flap;
namely, a slot on the main wing 0.20c behind the leading
edge, and a slot on the flap itself at 0.73c (or 0.03c
behind the hinge). The results for a range of flap
deflections are shown in figures 14 and 15. For the
slot at 0.20c, the maximum lift for all the flap angles
is somewhat greater than for the wing without the flap
and, in all cases, the stall occurs at an angle of
attack above 30°. The slope of the lift curves, however,
is less than for the plain wing (0° flap setting) prob-
ably because of separation of the flow on the flap itself.

The curves for the slot on the flap (fig. 15) show
about the same slope as for the plain wing; however,
because of increased flap effectiveness, these curves for
the several flap angles are shifted about three times as
much as those for the slot at 0.20c (fig. 14). Only two
of the flap angles - 30° and 45° - gave maximum lift
coefficients greater than that for the best condition of
the plain wing with boundary-layer control (fig. 12), but
these maximum lift coefficients were obtained at very
much lower angles of attack, a characteristic that is of
considerable practical importance.

Because slot locations near the flap hinge thus
appear to be effective in maintaining high lift-curve
slope and high flap effectiveness, and those near the
leading edge are more effective in holding the flow at
high angles of attack, two slots, one at the front and
one at the rear, appear to be desirable.

Figure 16 shows maximum lift coefficient plotted
against ideal-blower drag coefficient for the most
efficient arrangements of the plain and flapped wing.
All the flap arrangements appear to be more efficient
than the plain wing, and the highest maximum lift (2.84)
was obtained when the slot was located on the flap just
behind the hinge.

Zap flap. - Results for the wing with the Zap flap
(fig. 17) are similar to those for the plain wing. The
slope of the lift curve is very little affected by

boundary-layer control, and the increase in lift with
control is obtained by delaying the stall to higher
angles of attack; for this purpose the slot at 0.20c
appears most effective.

Figure 18 shows maximum lift coefficient plotted
against ideal-blower drag coefficient. The Zap flap
with suction at 0.20c provided the highest lift coef-
ficient (3.2) obtained with a single suction slot in
these tests of the high-aspect-ratio wing. A combination
of two slots, at 0.05c and 0.73c, however, yielded a
slightly higher maximum lift coefficient but required a con-
siderably larger ideal-blower drag coefficient through-
out the entire range. A comparison of the maximum lift
coefficient obtained without a control slot with the
values obtained with the slot located near the leading
edge indicates that a small amount of power is required
to overcome the adverse effects of the slots. A com-
parison with the best of the other arrangements is shown
in figure 19.

Drag reduction for take-off and climb.- Some
additional tests of the plain wing were made with a slot
at 0.91c in order to investigate the possibility of
achieving a net increase in lift-drag ratio for the range
of lift coefficients of interest for climb and take-off.
These tests were made at a tunnel speed of 80 miles per
hour. The rear slot location appeared the most logical
with respect to economy of blower power, because the
velocity in the boundary layer is lowest in that region
and the pressure on the wing is highest. The exhaust
velocity at the rear of the fuselage was approximately
equal to the tunnel velocity for these tests.

The polars with and without control are compared in
figure 20 with the induced-drag polar $C_{D_i}$ for a wing
of aspect ratio 6. The total drag coefficient $C_{D_T}$ is
the sum of the measured drag coefficient $C_D$ and ideal-
blower drag coefficient $C_{D_{b(ideal)}}$. Because of the
large reduction in profile drag in the range of lift
coefficients corresponding to take-off and climb, a net
increase is shown in the lift-drag ratio for this range.
The minimum drag is increased somewhat by boundary-layer
control.

## SUMMARY OF RESULTS

Results are presented of boundary-layer-control tests of two wings to determine the increase in lift obtained and the power required for the blower. One wing, tested with both pressure and suction, had a 6.5-foot span, a 5.5-foot chord, and an airfoil section of 0.30-chord maximum thickness and was fitted with large end plates. The other wing, tested with suction only, used an NACA 2415 airfoil and had a 16-foot span, a 2.67-foot chord, and was tested without a flap, with a plain flap, and with a Zap flap. A summary of the results follows:

1. For the stub wing of 0.30-chord maximum thickness:

(a) A lift coefficient of about 3.2 was obtained with a suction slot at 0.54 chord and at a power expenditure corresponding to a blower drag coefficient of 0.07.

(b) Nearly the same lift coefficient was obtained with a pressure slot at 0.42 chord as with the slot at 0.54 chord, but the blower drag coefficient was several times as much.

(c) A single large suction slot near the midchord of the wing was more effective than any multiple-slot arrangement when the same suction was applied to all slots.

2. For the NACA 2415 wing:

(a) With the plain wing or the wing with a Zap flap, the highest maximum lift coefficients were obtained with the slot between 0.11 and 0.20 chord from the leading edge, with ideal-blower drag coefficients of about 0.3. The maximum lift coefficients were about 2.6 and 3.2 for the plain wing and for the wing with the Zap flap, respectively.

(b) With a plain flap, least power for the highest maximum lift obtained was required when the slot was located on the flap just behind the hinge, and the angles of attack required for maximum lift were more nearly in the practical range than those required by the plain wing.

(c) With a plain flap, slot locations near the flap hinge appear to be effective in maintaining high lift-curve slope and high flap effectiveness, but those near the leading edge are more effective in holding the flow at high angles of attack.

(d) With the plain wing with a slot at 0.91 chord an appreciable increase in the lift-drag ratio (where the drag included the blower drag) occurred for the take-off and climb range.

Langley Memorial Aeronautical Laboratory
    National Advisory Committee for Aeronautics
        Langley Field, Va., July 23, 1945

REFERENCES

1. Bamber, Millard J.:  Wind Tunnel Tests on Airfoil Boundary Layer Control Using a Backward-Opening Slot.  NACA Rep. No. 385, 1931.

2. Schrenk, Oskar:  Experiments with a Wing from which the Boundary Layer is Removed by Suction.  NACA TM No. 634, 1931.

TABLE I.- ORDINATES FOR 30-PERCENT-THICK WING

| X (percent chord) | Upper surface (percent chord) | Lower surface (percent chord) |
|---|---|---|
| 0 | 10.08 | 10.08 |
| 1.25 | 15.58 | 6.05 |
| 2.5 | 18.00 | 4.50 |
| 5.0 | 21.30 | 2.70 |
| 7.5 | 23.75 | 1.61 |
| 10.0 | 25.70 | .89 |
| 15.0 | 28.10 | .29 |
| 20.0 | 29.40 | .045 |
| 30.0 | 30.00 | 0 |
| 40.0 | 28.55 | |
| 50 | 25.35 | |
| 60 | 21.15 | |
| 70 | 16.50 | |
| 80 | 11.28 | |
| 90 | 5.70 | |
| 95 | 2.79 | |
| 100 | 0 | |
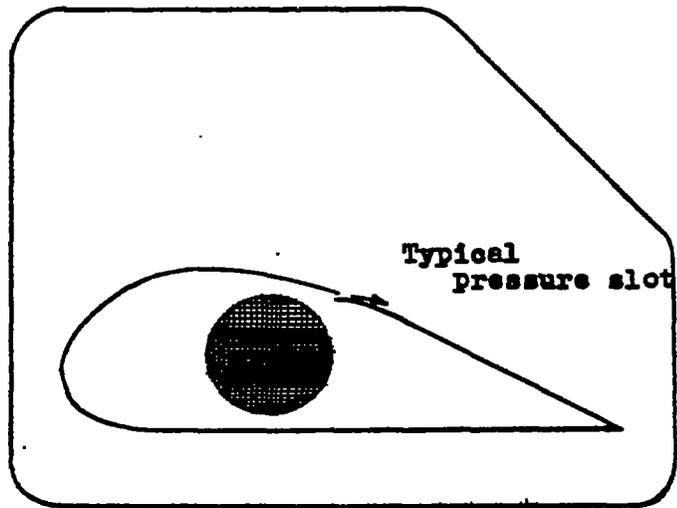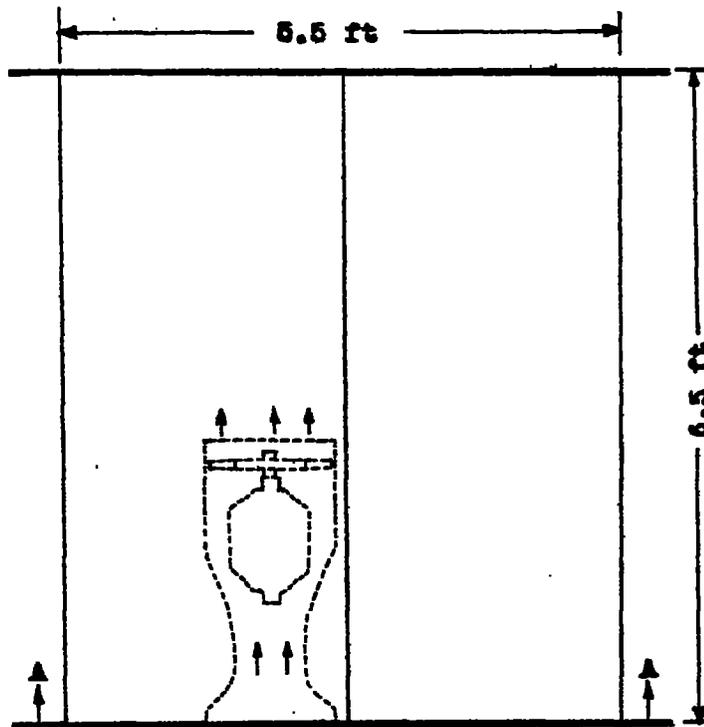
Section A - A

Figure 1.- Stub wing of 0.30c thickness and blower
for boundary-layer-control tests with pressure-
slot arrangement shown.
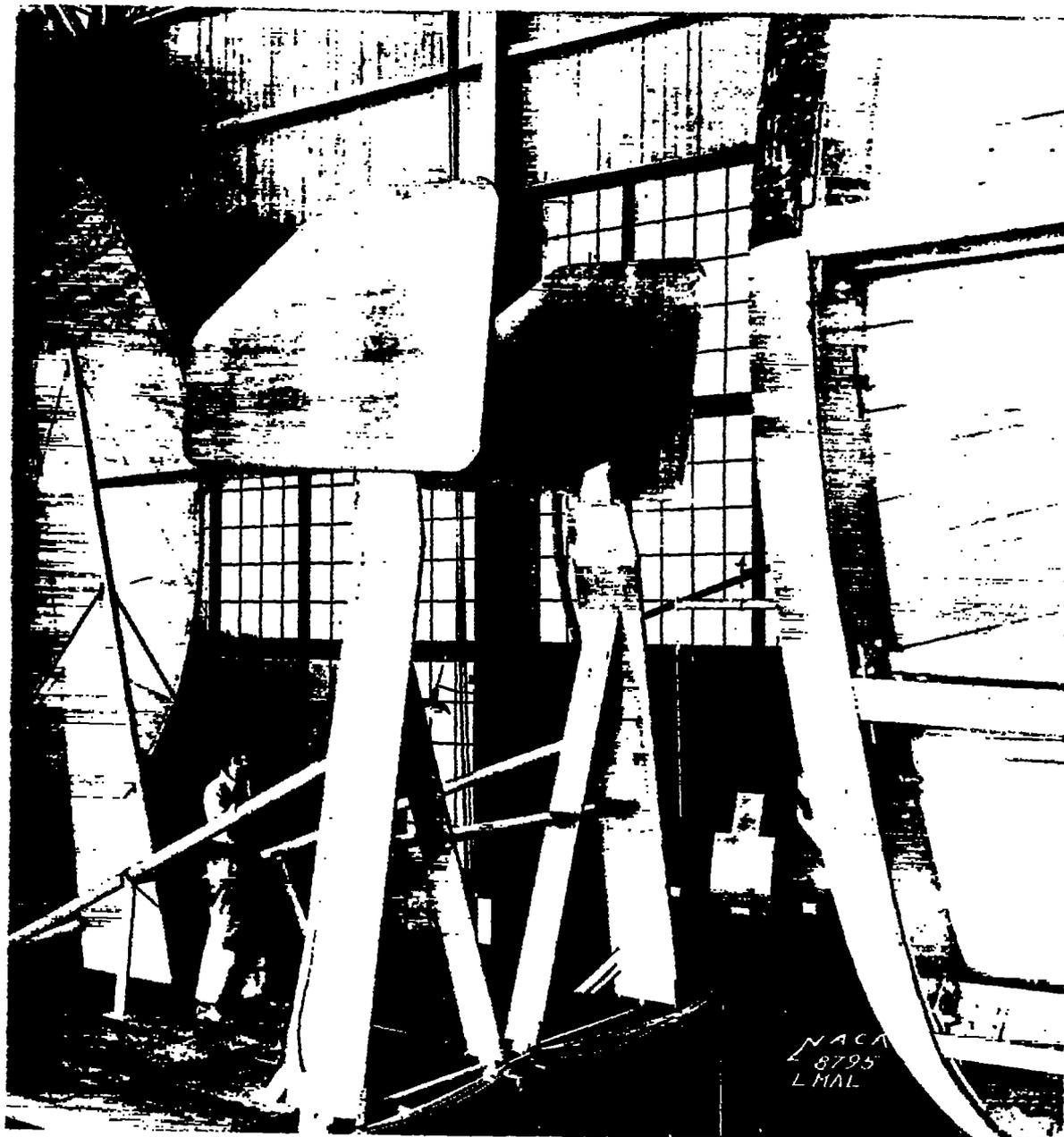
Figure 2.- Stub wing of 0.30c thickness mounted in the
Langley propeller-research tunnel.
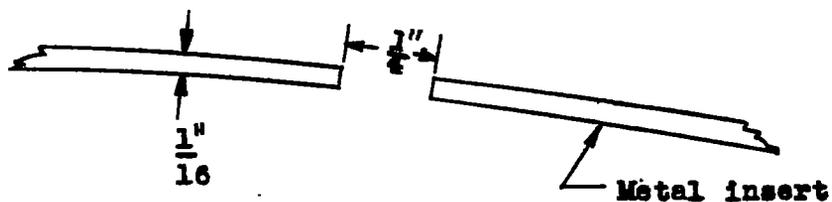
Typical normal-opening suction slot
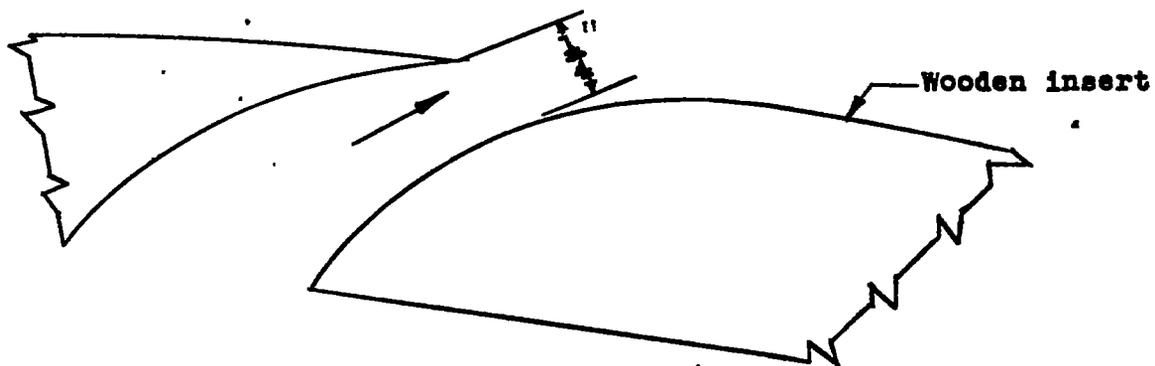


Typical backward-opening pressure slot

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Figure 3.- Boundary-layer-control slot configurations.

Figure 4.- NACA 2415 wing model mounted in the Langley propeller-research tunnel.

Fig. 4
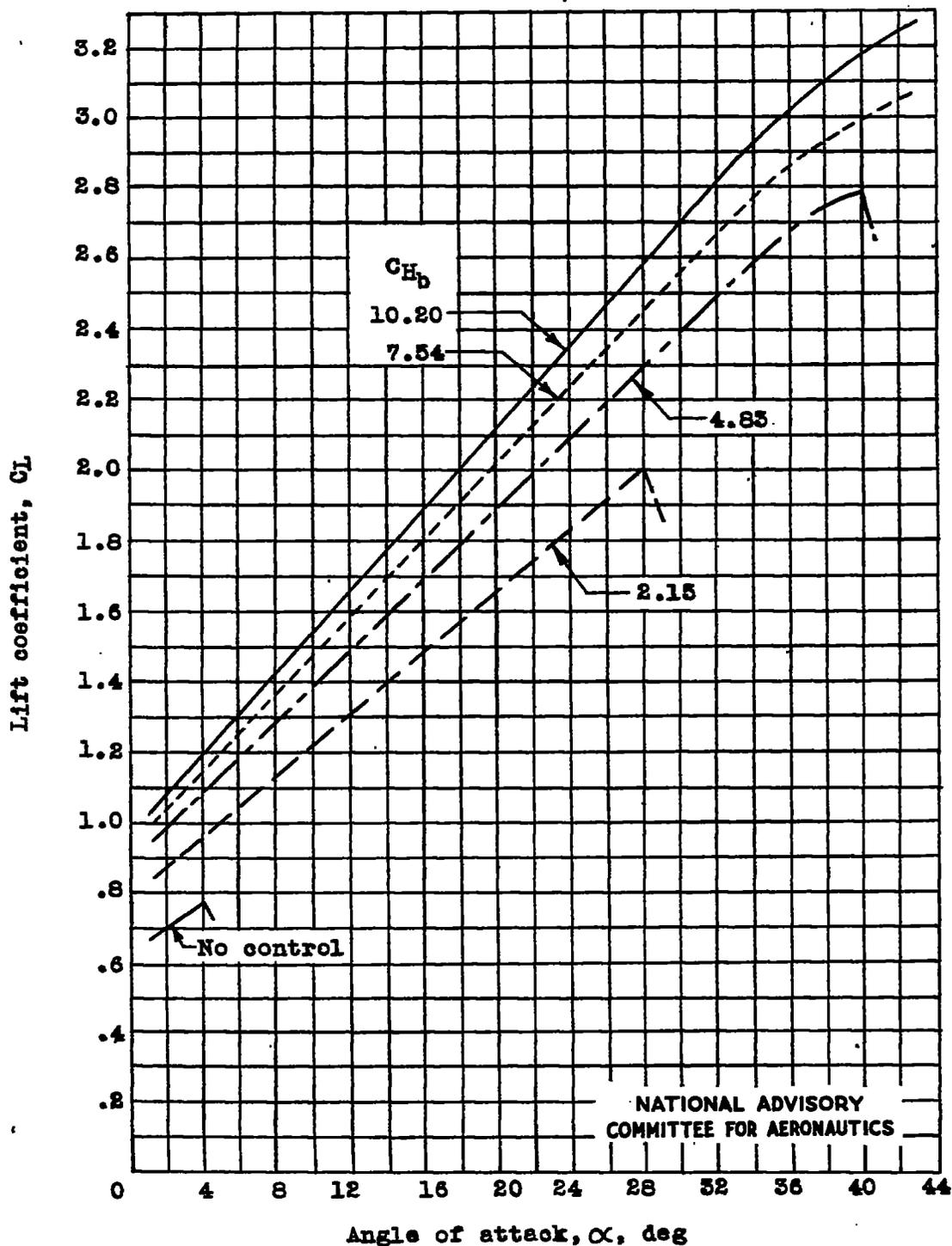
Figure 5.- Lift characteristics of the stub wing of 0.30c thickness with 0.0075c backward-opening pressure slot at 0.42c.

Fig. 6
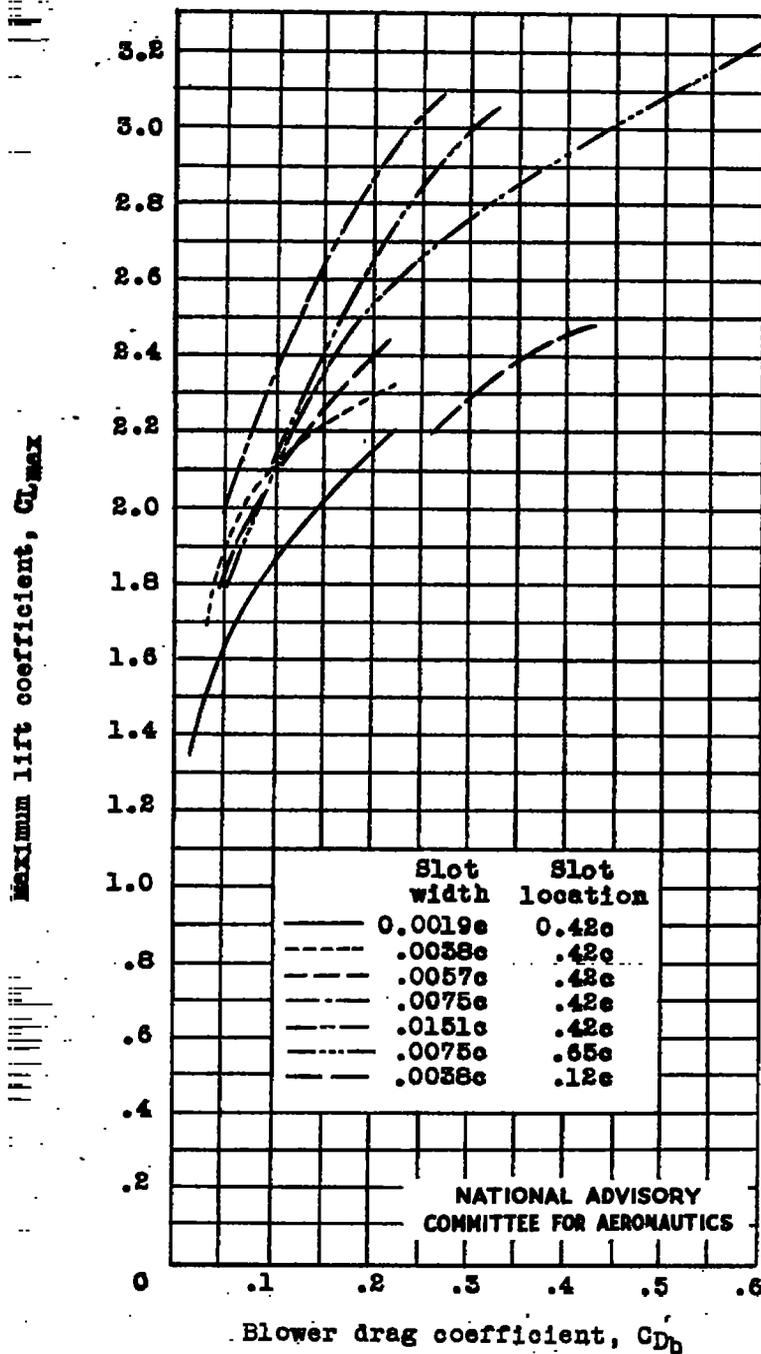
Figure 6.- Variation of maximum lift coefficient with blower drag coefficient for the stub wing of 0.30c thickness with several single-pressure slots.
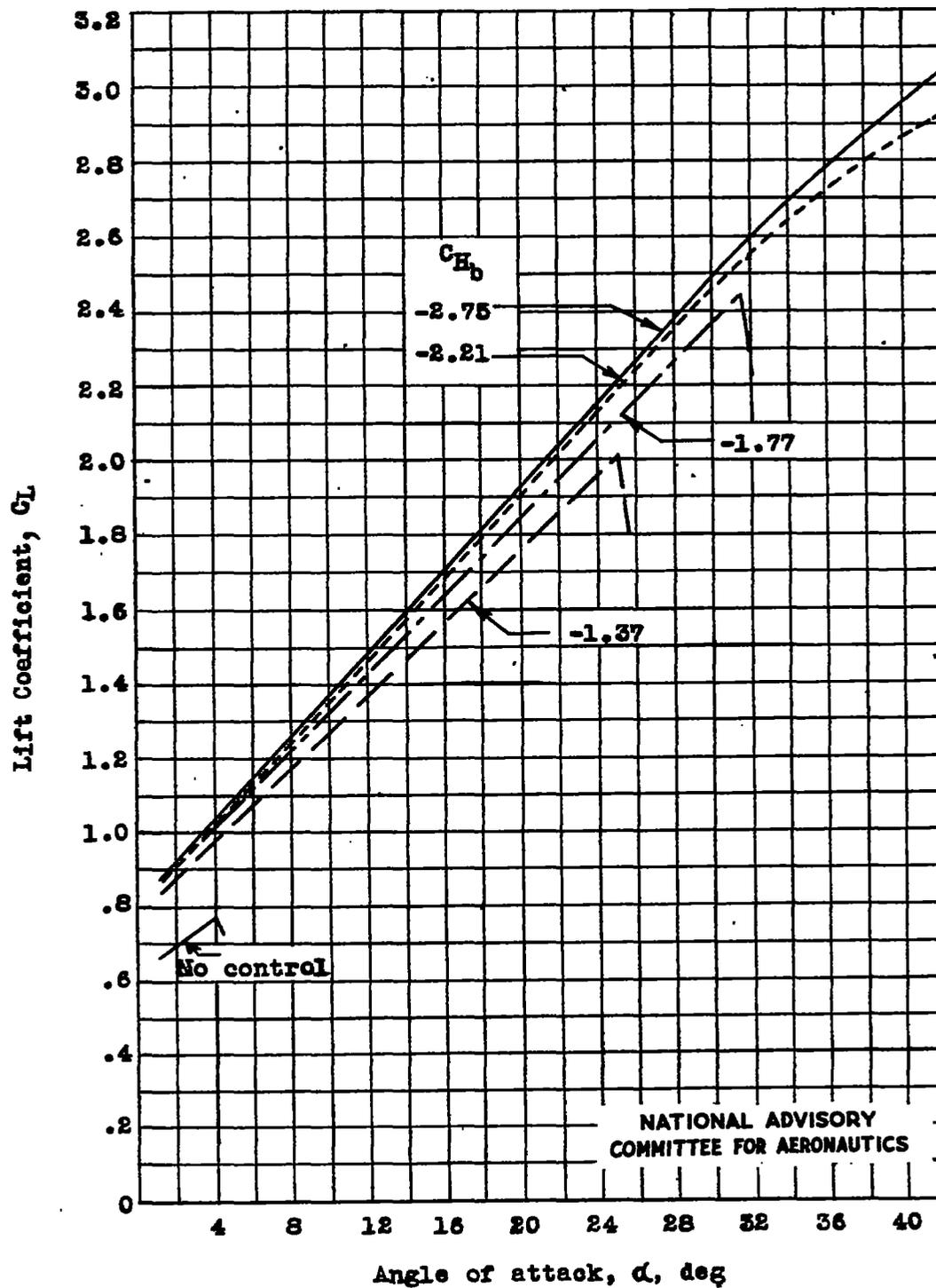
Figure 7.- Lift characteristics of the stub wing of
0.30c thickness with 0.0455c normal-opening suction
slot at 0.54c.

Fig. 8                                    NACA TN No. 1007
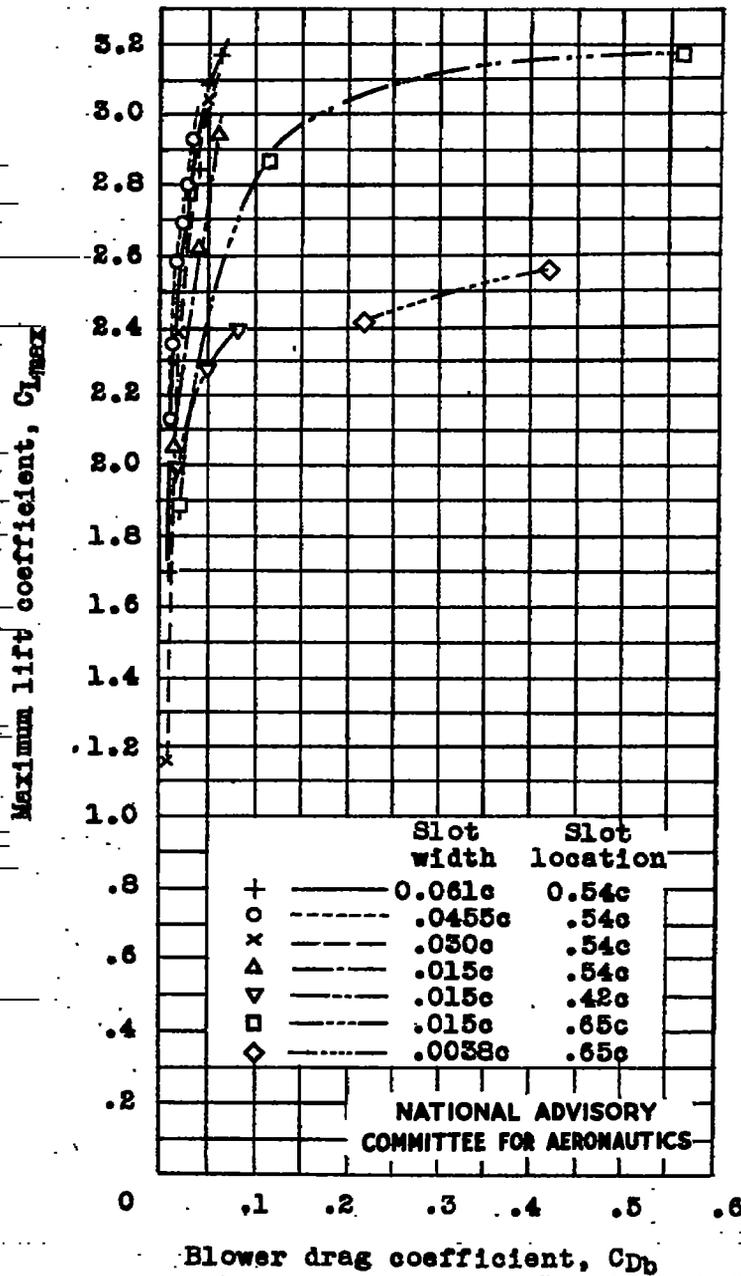


Figure 8.- Variation of maximum lift coefficient
with blower drag coefficient for the stub
wing of 0.30c thickness with several
single normal-opening suction slots.
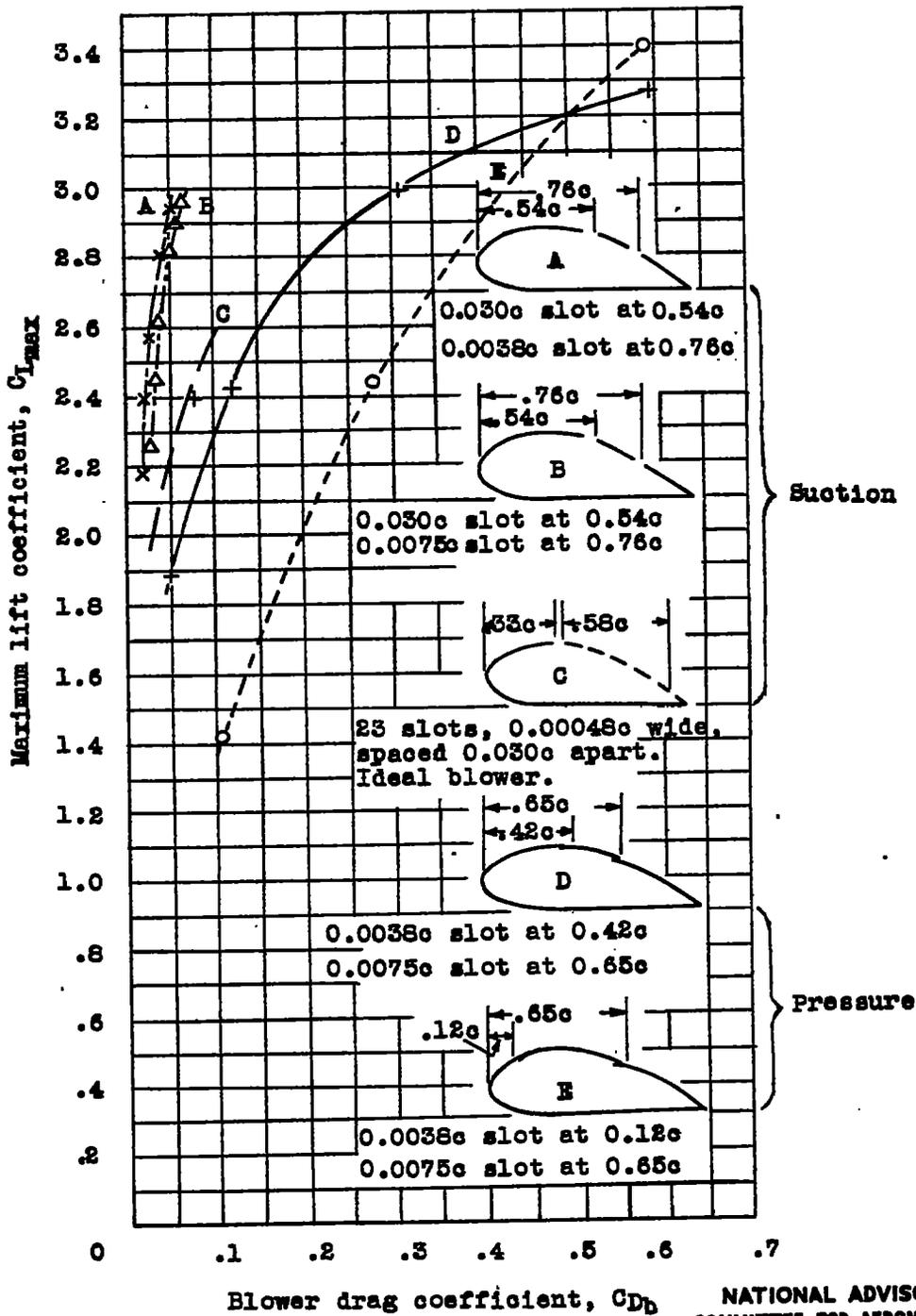
Figure 9.- Comparison of maximum lift coefficients
for several multiple-slot arrangements on the
stub wing of 0.30c thickness.

Fig. 10                                                    NACA TN No. 1007
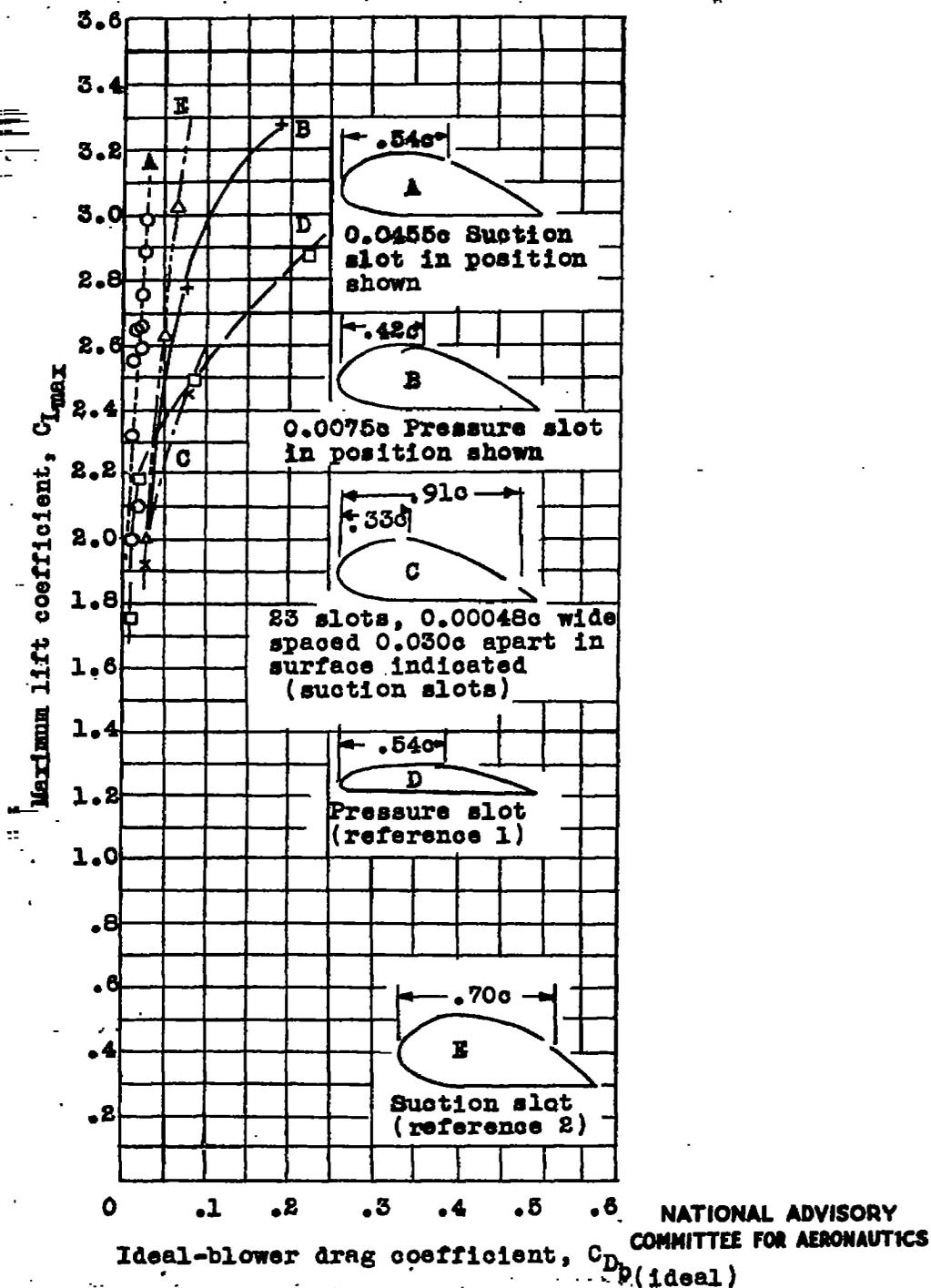


Figure 10.- Comparison of maximum lift coefficients of the stub wing of 0.30c thickness with values obtained from references 1 and 2 for various single-slot arrangements.

Slot width

0.0455c

.061c

.061c

.015c

.061c

.030c

Maximum lift coefficient, $C_{L_{max}}$

3.6

3.2

2.8

2.4

2.0

1.6

1.2

.8

.4

0

.01                    .02

Volumetric coefficient, $C_Q$

×  ————— Suction slot at 0.54c
○  --------- .0075c pressure slot at .65c
+  —·—·— 23 slots, .00048c wide, spaced
        .030c between .33c and .91c
△  ——— Suction (reference 2)
□       Pressure (reference 1)

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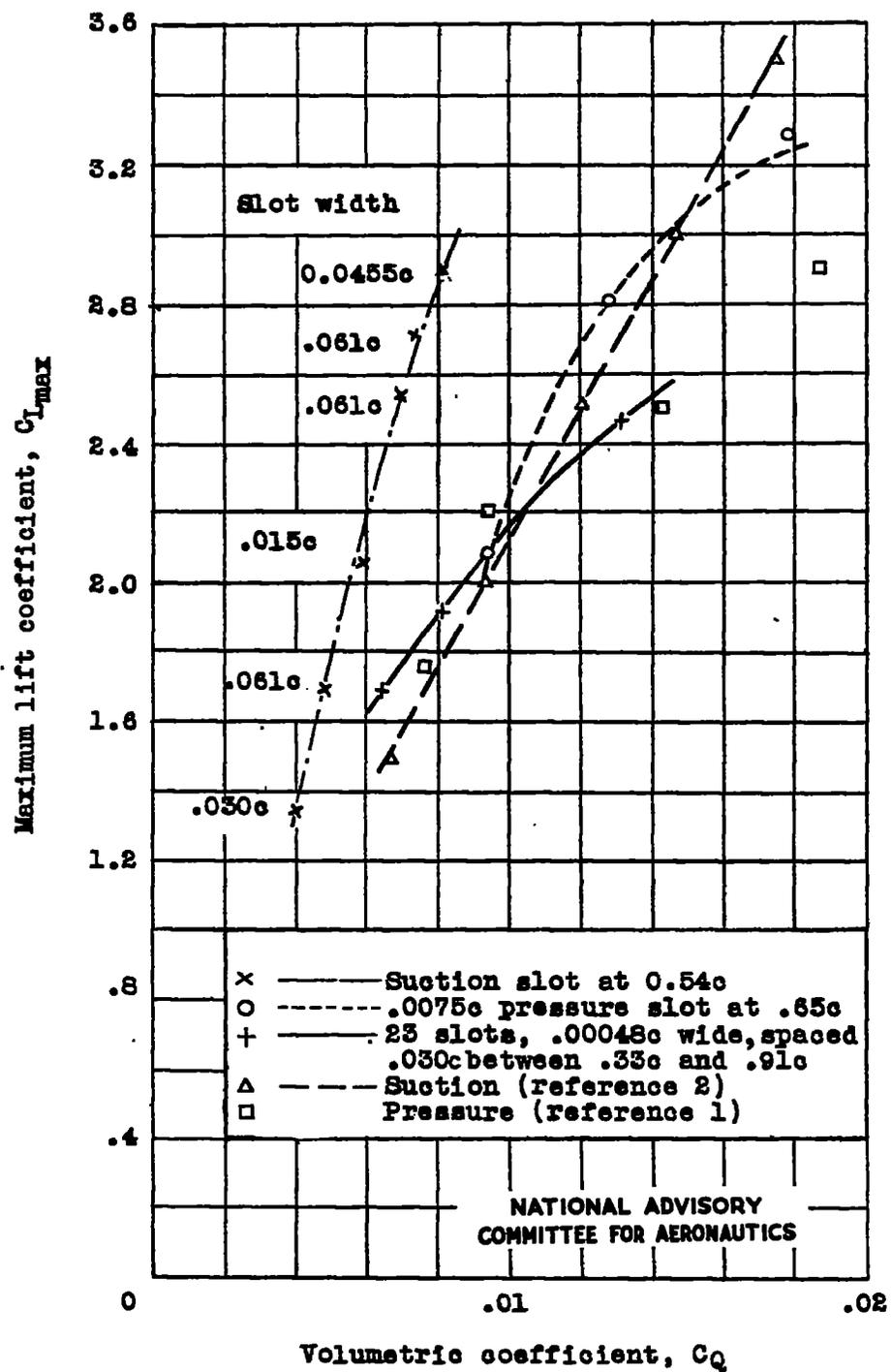
Figure 11.- Comparison of maximum lift coefficients
for various slot arrangements on the stub wing of
0.30c thickness with values obtained from tests
in references 1 and 2.

Fig. 12
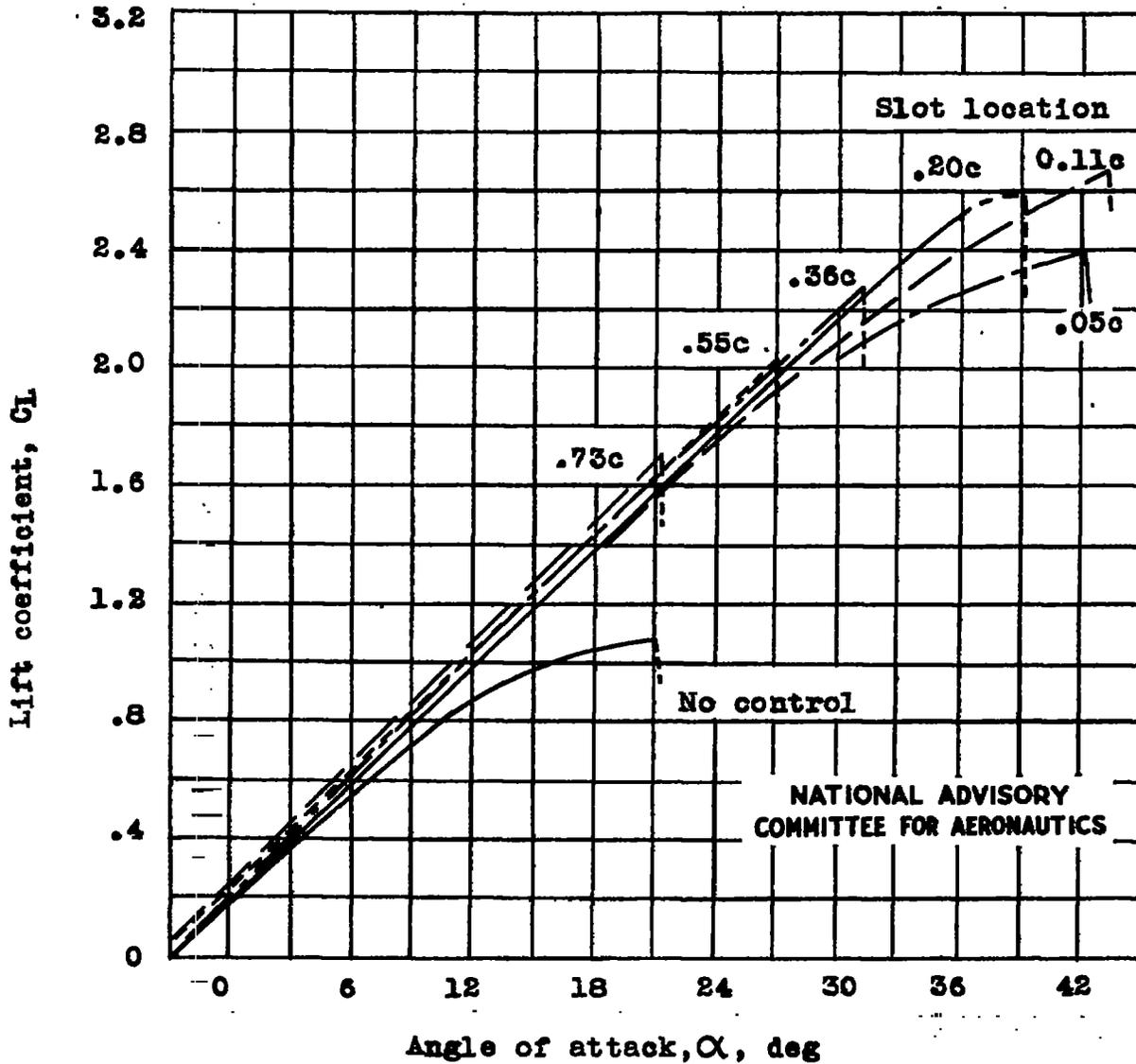
Figure 12.- Lift curves of the NACA 2415 plain wing for
six slot locations with constant blower speed.

Ideal-blower drag coefficient, $C_{D_b \text{(ideal)}}$
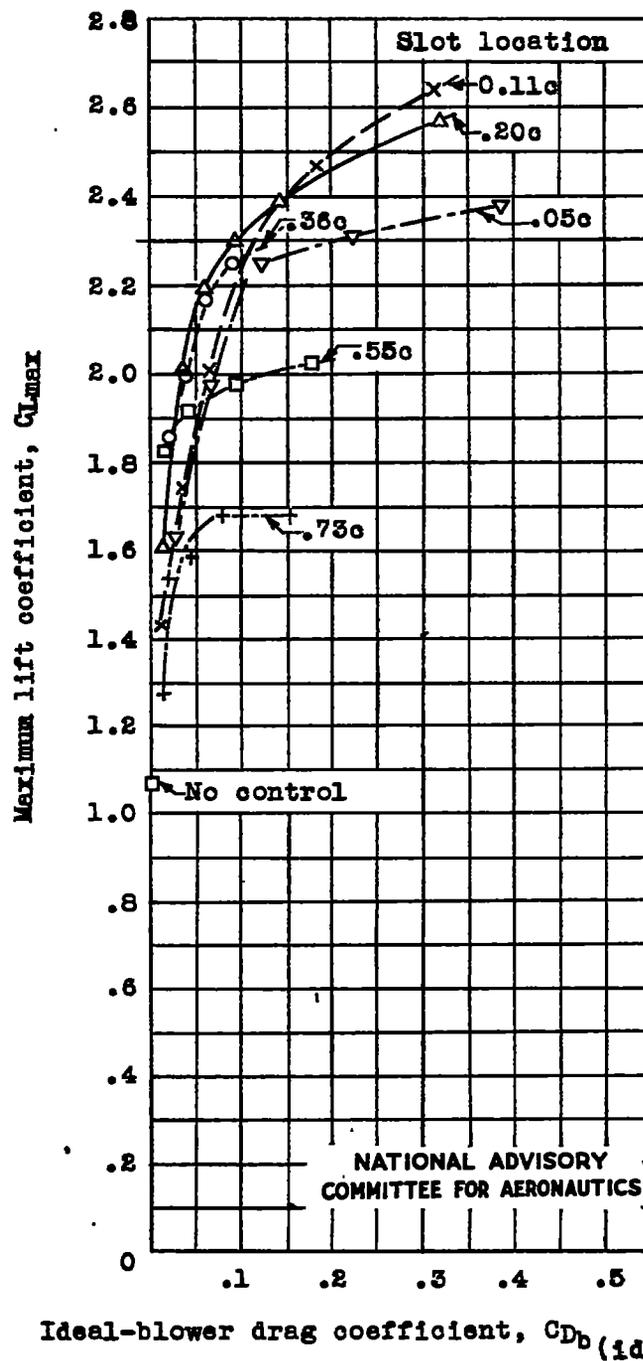
Figure 13.- Variation of maximum lift coefficient of the NACA 2415 plain wing with ideal-blower drag coefficient and slot location.
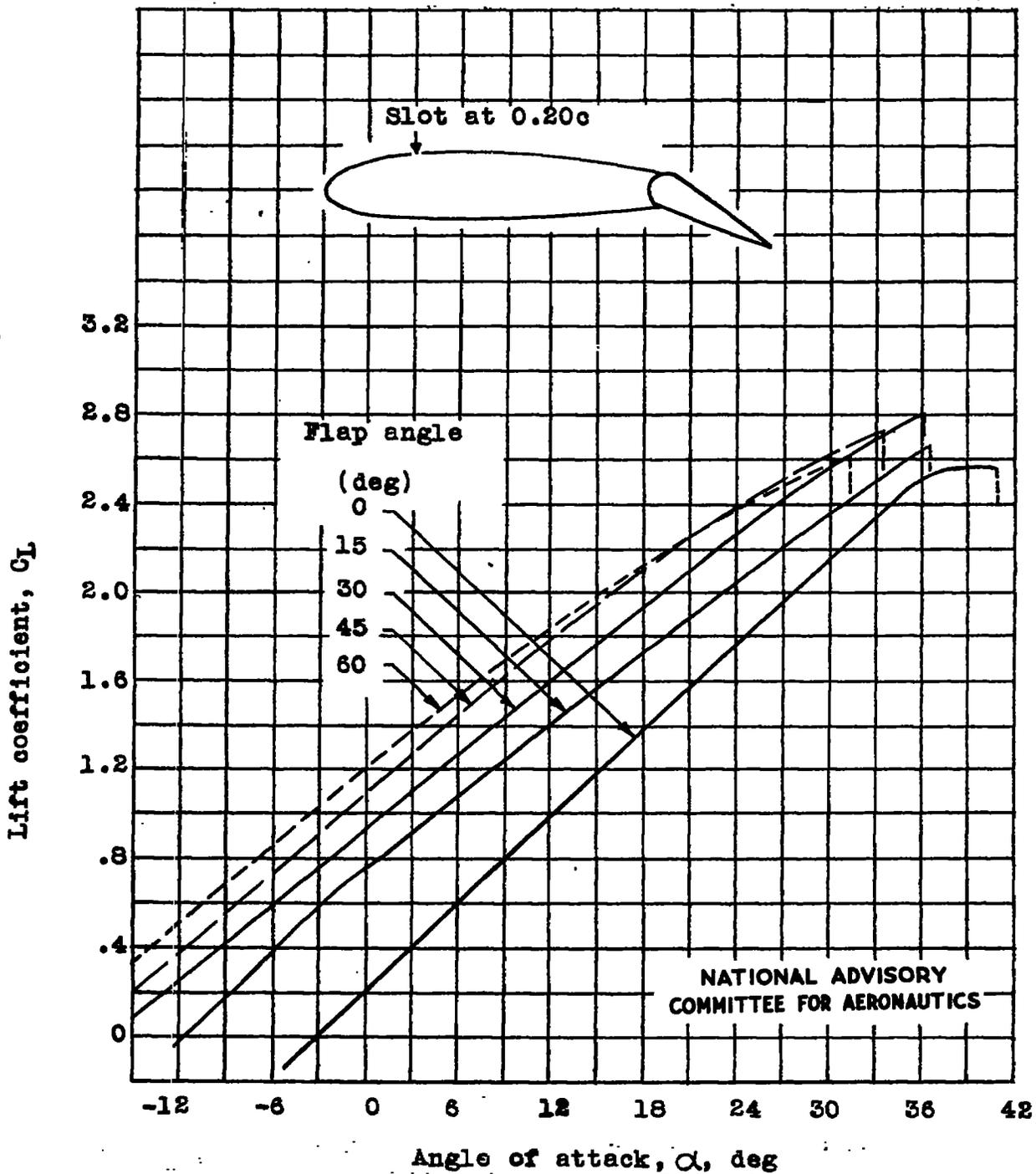
Figure 14.- Lift curves with slot on main wing.  NACA 2415
wing with plain flap; blower speed, constant.
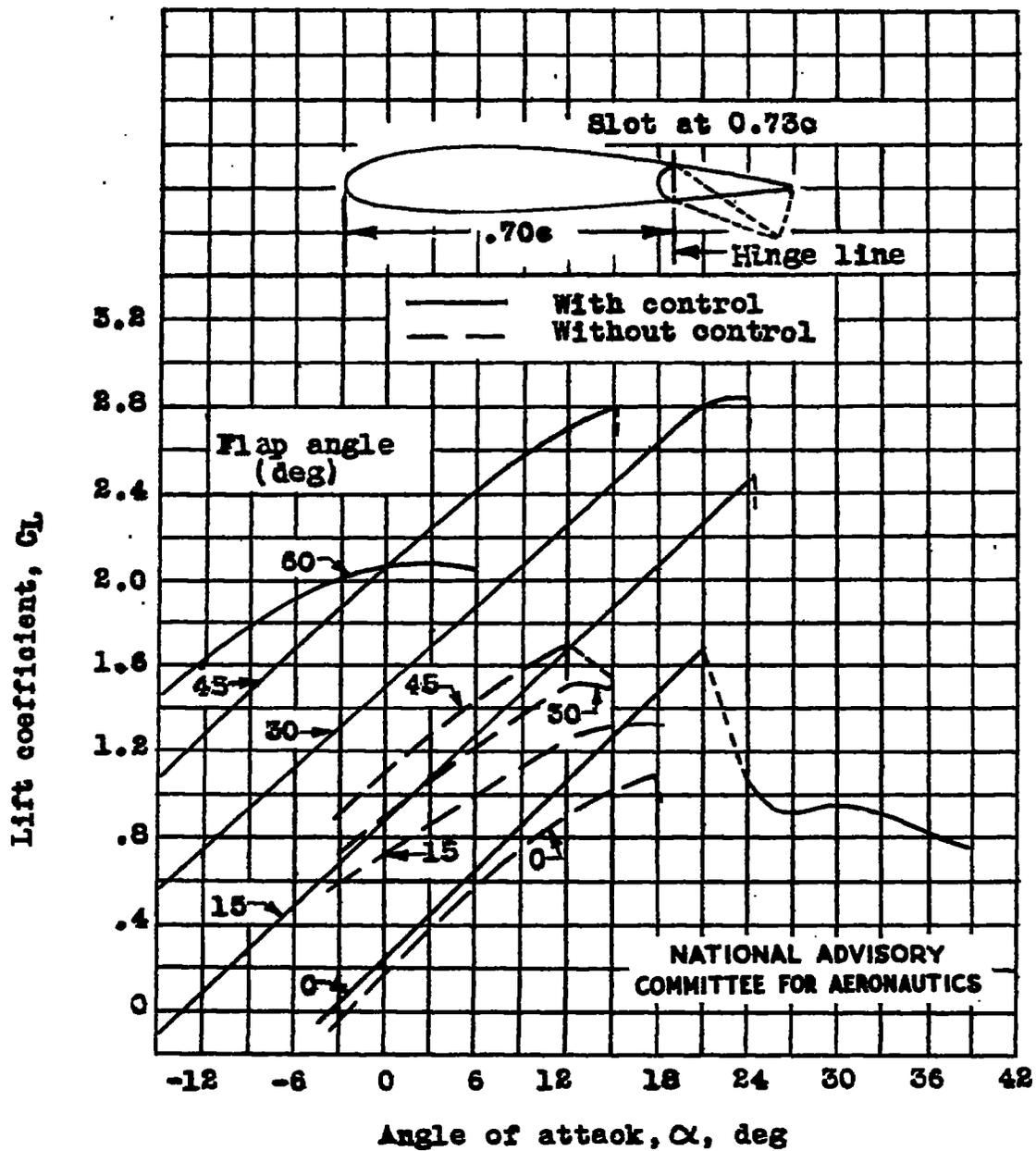
Figure 15.- Comparison of lift with and without
boundary-layer control with slot on flap.
NACA 2415 wing with plain flap; blower speed,
constant.

Fig. 16

NACA TN No. 1007
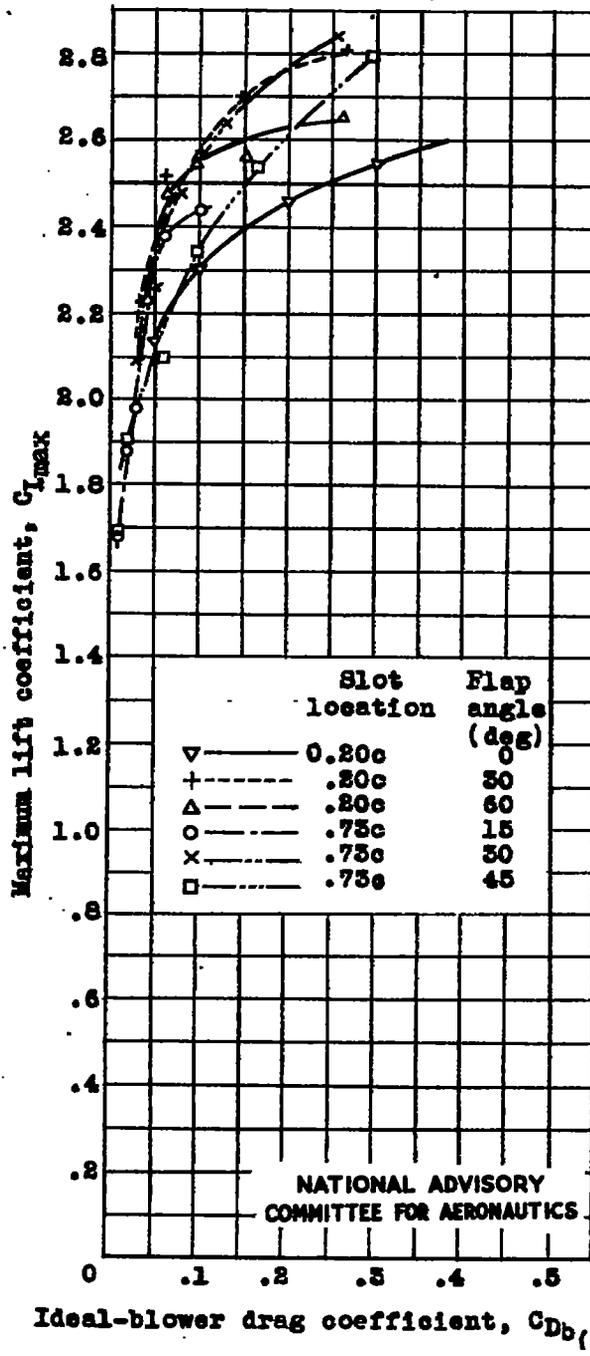


Figure 16.- Variation of maximum lift
coefficient with ideal-blower drag
coefficient. NACA 2415 wing with
plain flap.
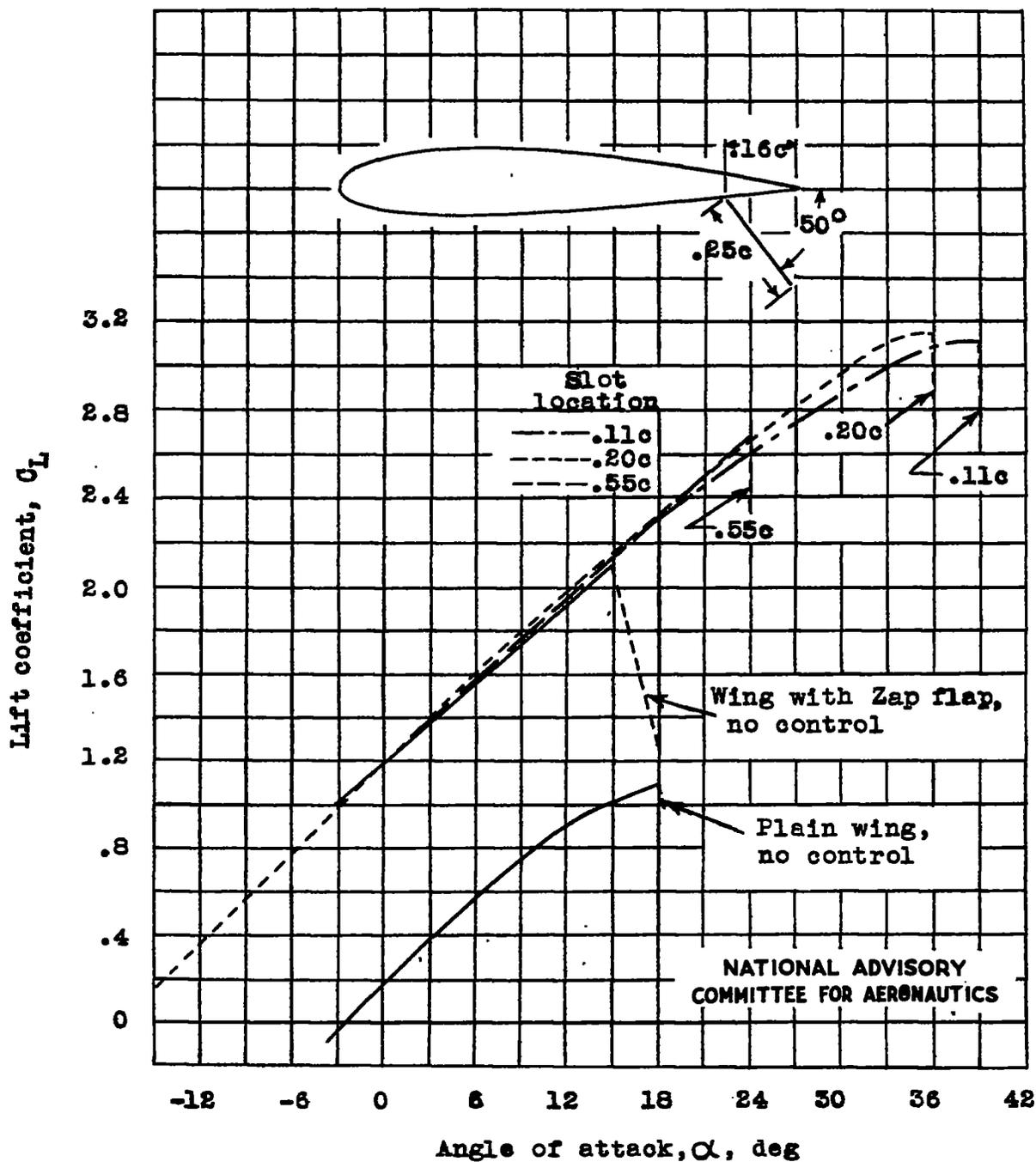
Figure 17.- Lift curves with and without boundary-layer
control. NACA 2415 wing with Zap flap deflected 50°
to the chord line; blower speed, constant.

Fig. 18                                             NACA TN No. 1007



Ideal-blower drag coefficient, $C_{D_{b(ideal)}}$
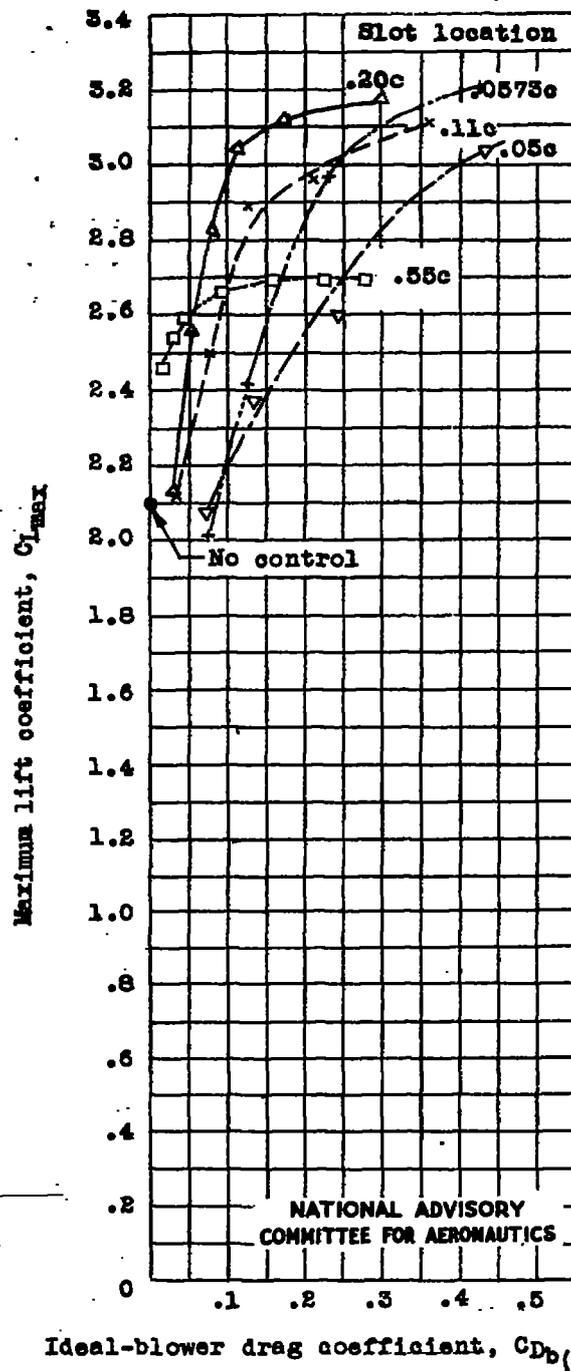
Figure 18.- Variation of maximum lift coefficient
with ideal-blower drag coefficient on the NACA
2415 wing with Zap flap deflected 50° to the
chord line.
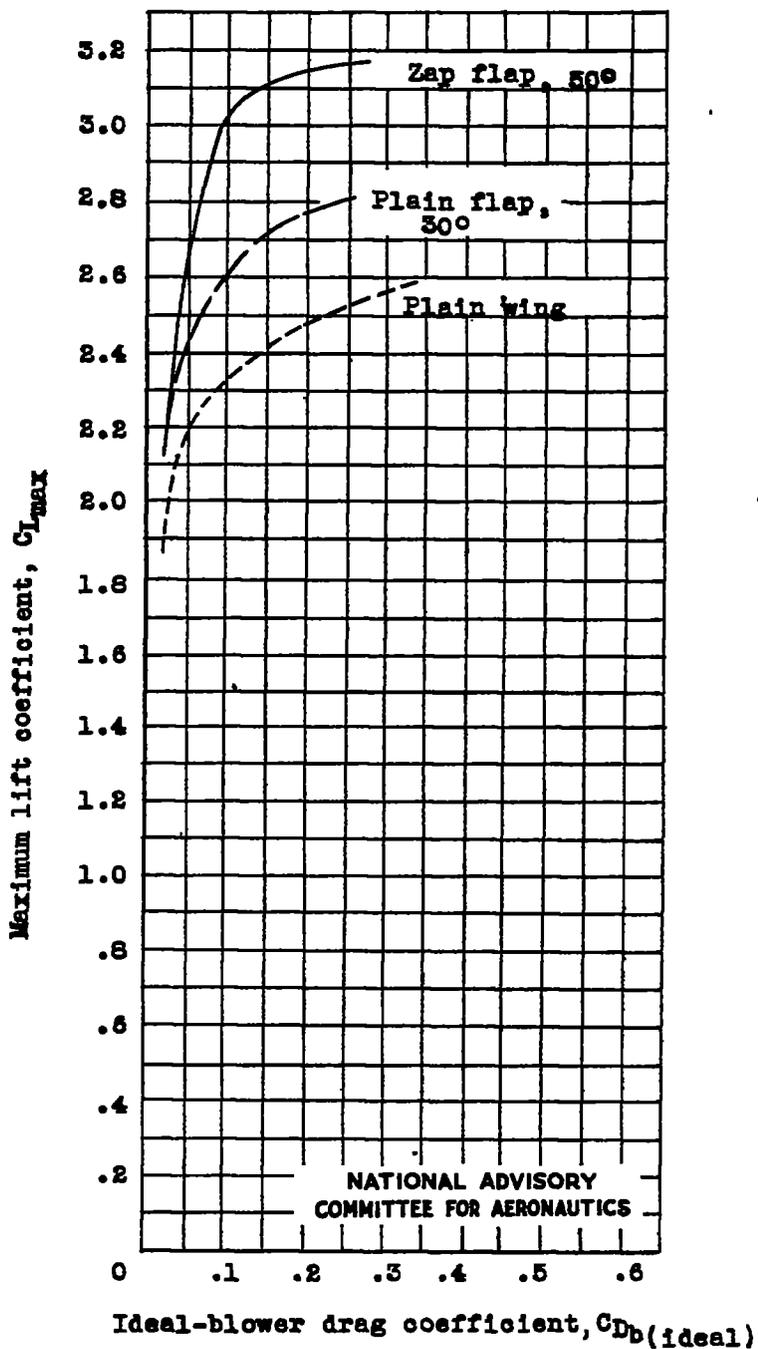
Figure 19.- Comparison of maximum lift coefficient
obtained for the NACA 2415 plain wing, for the
wing with a plain flap, and for the wing with
a Zap flap.

Fig. 20                                            NACA TN No. 1007
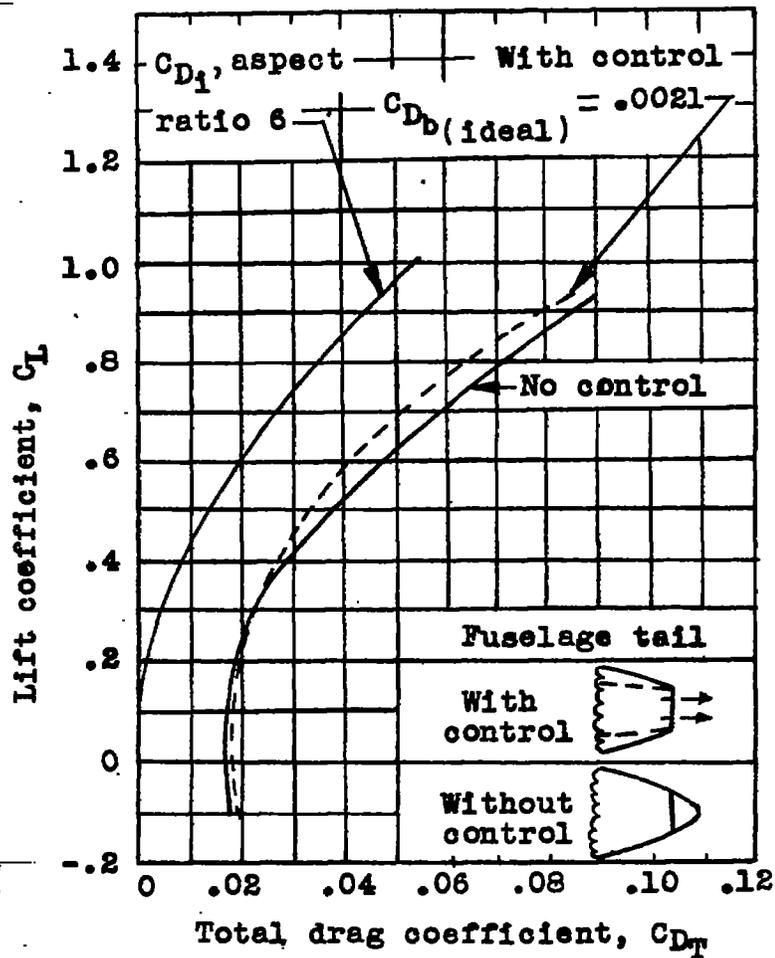


Figure 20.- Lift-drag polar for the
NACA 2415 plain wing with slot
at 0.91c.

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